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The Fundamental Nucleon-Nucleon Interaction: Probing Exotic Nuclear Structure using GEANIE at LANSCE/WNR

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Final Report on the Laboratory Directed Research and Development Project 98-LW-051

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Introduction

The initial goal of this project was to study the in-medium nucleon–nucleon interaction by testing the fundamental theory of nuclear structure, the shell model, for nuclei between ^{80}Zr and ^{100}Sn. The shell model predicts that nuclei with "magic" (2, 8, 20, 28, 40, 50, and 82) numbers of protons or neutrons form closed shells in the same fashion as noble gas atoms [may49]. A "doubly magic" nucleus with a closed shell of both protons and neutrons has an extremely simple structure and is therefore ideal for studying the nucleon–nucleon interaction. The shell model predicts that doubly magic nuclei will be spherical and that they will have large first-excited-state energies (~1 to 3 MeV). Although the first four doubly-magic nuclei exhibit this behavior, the $N = Z = 40$ nucleus, ^{80}Zr, has a very low first-excited-state energy (290 keV) and appears to be highly deformed. This breakdown is attributed to the small size of the shell gap at $N = Z = 40$. If this description is accurate, then the $N = Z = 50$ doubly magic nucleus, ^{100}Sn, will exhibit "normal" closed-shell behavior. The unique insight provided by doubly-magic nuclei from ^{80}Zr to ^{100}Sn has made them the focus of tremendous interest in the nuclear structure community.

However, doubly-magic nuclei heavier than ^{56}Ni become increasingly difficult to form due to the coulomb repulsion between the protons which favors the formation of neutron-rich nuclei. The coulomb repulsion creates a "proton drip-line" beyond which the addition of any additional bound protons is energetically impossible. The drip line renders the traditional experimental technique used in their formation, the heavy-ion reaction, less than ideal as a method of forming doubly-magic nuclei beyond ^{80}Zr. The result has been a lack of any new spectroscopic information on doubly magic nuclei in more than a decade [lis87]. Furthermore, uncertainties in reaction dynamics modeling made it difficult for the nuclear science community to predict the cross section for forming these highly-neutron deficient nuclei. Therefore, we decided to try a new approach to forming highly-neutron deficient nuclei with the hope of both gaining spectroscopic information for nuclei near ^{100}Sn, and also gaining insight into reaction dynamics at high ($E_x > 200$ MeV) incident nucleon energy.

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Year I: FY98

In 1998 we pioneered this new approach. We used the Los Alamos Neutron Science Center/Weapon Neutron Research (LANSCE/WNR) neutron source to produce high-energy ($E_n \leq 250$ MeV) beams of neutrons which in turn induced (n,xn) reactions with $x \geq 13$. Low-lying levels in the resulting neutron-deficient nuclei were then observed using the first large γ-ray spectrometer ever located at a high-energy neutron facility; GEANIE. Our first experiment succeeded in studying highly neutron-deficient Platinum nuclei using (n,xn) reactions with x ≤ 15 (figure 1a), and resulted in our first refereed publication [ber98-attached]. In addition to giving insight into reaction dynamics this data also provided information regarding the population of different excited states in the reaction product nuclei as a function of increasing neutron energy (figure 1b). This program was highly leveraged by the use of Physical Data Research Program funds to assemble the array for the ^{239}Pu(n,2n) cross section effort [ber00].

The ^{112}Sn GEANIE experiment

Our initial goal was to study ^{100}Sn using the ^{112}Sn(n,13n) reaction. However, significant uncertainties existed concerning the ability to produce such a highly neutron-deficient nucleus due to the lack of a detailed understanding of the underlying reaction dynamics at such large incident neutron energies. Although our first results indicated that calculations underestimated reaction cross sections by more than 50% [ber98], there was no certainty that this trend would continue as the proton-drip line was approached. Therefore, a strong secondary motivation for our experiments was to gain insight into reaction dynamics at high incident particle energy.

During the first year of this project included completing and reporting a preliminary analysis of a late-FY97 test run at GEANIE using a ^{112}Sn target and making major improvements to GEANIE's electronics. The lightest Sn nucleus we succeeded in observing was ^{108}Sn (the (n,5n) channel). The rapid drop-off in production cross section is most likely due to the sharp decrease in the proton binding energy as the proton drip-line is approached. Although we did not succeed in identifying ^{100}Sn we gathered a large data set of neutron-induced partial γ-ray cross sections up to $E_n \leq 250$ MeV. Figure 2 shows the reaction products observed in this experiment. The data set allowed us to compare our data with the predictions of two state-of-the-art reaction models, HMS-ALICE and GNASH [mcg99]. Figure 3 shows cross sections for several reaction products (as deduced from the first excited state to ground state transition) and the results of both HMS-ALICE and GNASH. These results were presented at the Division of Nuclear Physics of the American Physical Society Meetings in October 1998 [mcn98] and October 1999 [mcg99].

In addition during the first year we made a number of improvement to the GEANIE electronics which resulted in a) a factor of 2 increase in the detector throughput, b) the addition of 6 more detectors (bringing our total to 26), c) an increase in the neutron time and energy resolution by a factor of 3, and d) the addition of a 100 millisecond range clock that allow the use of gamma rays observed during beam-off intervals, to measure reaction yield and isomeric state decay. These capabilities will be described in the next section.

Year II: 1999

In the second year we focused are efforts at nuclei further from the proton line near ^{80}Zr. We proposed and had accepted two experiments to study neutron deficient nuclei in this vicinity. The first experiment used the ^{24}Mg(^{58}Ni,2n) and the premier international gamma-ray spectrometer, GAMMASPHERE at Argonne National Laboratory to study the doubly-magic nucleus ^{80}Zr. It became clear to us this year that neutron beams would not be able to form the most neutron-deficient of nuclei. However, the capability of GEANIE as a tool for gaining unique insight into nuclear reaction mechanisms was clearly demonstrated.

The ^{80}Zr GAMMASPHERE Experiment

In October 1999 an experiment was run at ANL to measure the structure of ^{80}Zr using the ^{24}Mg(^{58}Ni,2n) reaction used a decade earlier by Lister et al., [list88]. The structure of nuclei near ^{80}Zr has long been a subject of intense debate between theorists since some models predict extreme deformation while others predict a less symmetric triaxial shape. The purpose of this experiment was to gain insight into the shape of ^{80}Zr through observation of its low-lying level scheme.

The experiment was eminently successful. Several new levels in ^{80}Zr were observed, and a large amount of additional insight was gained regarding the neighboring nucleus ^{80}Y. A tentative ^{80}Zr level scheme is shown in Figure 4. Two manuscripts are planned for publication in 2000.

The ^{92}Mo GEANIE experiment

The second approach used a ^{92}Mo target at GEANIE in an attempt to populate light-neutron-deficient Mo and Zr nuclei using (n,xn yp zα) reactions. The experiment was performed at the LANSCE-WNR spallation neutron source using the GEANIE spectrometer and a scattering sample of ^{92}Mo. Excitation functions and $\gamma\gamma$-coincidences for the in-beam data were analyzed, and the out-of-beam β-decay data were also analyzed.

Applying a gate on the time of the events corresponding to neutrons with energies between 1 and 8 MeV selected (primarily) events associated with the ^{92}Mo(n,n$'\gamma$) reaction. An additional 50 γ rays and 20 levels below 5 MeV excitation energy were added to the level scheme of ^{92}Mo from this data. These results were compared with recent shell-model calculations [Sin92] as shown in Figure 5. As can be seen, below 4 MeV the model reproduces well the level scheme. Above 4 MeV, however, the number of observed levels is far greater than calculated; this is attributed to the limited model space in the calculations and, for the negative-parity states, the procedure used in fitting the parameters of the Hamiltonian [Sin92]. A report on the spectroscopy of ^{92}Mo has been submitted to Physical Review C [Gar00a], and was the subject of a contribution to the Division of Nuclear Physics of the American Physical Society Meeting in Asilomar, CA in Oct. 1999 [Gar99a]. In addition, some preliminary results were presented at the Division of Nuclear Physics of the American Physical Society Meeting in Sante Fe, NM in Oct. 1998 [McN98], and at the 10^{th} International Symposium on Capture Gamma-ray Spectroscopy and Related Topics, Sante Fe, Sept. 1999 [You99,You00].

Reaction dynamics studies were also pursued. Excitation functions for neutron energies up to 250 MeV, normalized at one energy to the calculated cross section for the $2^+\rightarrow0^+$ transition in ^{92}Mo, were extracted for a total of 26 different isotopes, as display in Figure 6. The lightest isotope observed was ^{80}Sr via the (n,α2p7n/4p9n) reaction channel. The experimental data were compared with the results of GNASH calculations for the partial γ-ray cross sections. The calculations include compound nucleus, preequilibrium, multiple-preequilibrium, and direct reaction processes.

When all the data are viewed together, a consistent picture emerges as to the strengths and weaknesses in the present reaction cross section calculations. Below ~20 MeV, the calculations overall do a reasonably good job of reproducing the cross section to the various final channels. Problems can arise, however, from weaknesses in modeling the γ-ray cascade. Incomplete knowledge of the low-lying portions of the level schemes, and the effect of nuclear structure, can cause significant deviations between the calculated and experimental cross sections for individual γ rays. This is especially apparent in the case of ^{91}Nb, shown in Figure 7. The predicted cross section for the positive-parity levels is in good agreement with the data, whereas that for the negative-parity states is not. This is due to the assumption of equal level densities and spin distributions between positive- and negative-parity states. An examination of the low-lying levels in ^{91}Nb reveals this is not the situation.

At higher neutron energies, the poor agreement between the calculated and observed excitation functions appears to arise due to the poor description of the competition between α–particle emission and the corresponding 2p2n process. The gross over-prediction for higher neutron energies of the α-emission cross section depletes cross section available for other reaction channels. As an example, at 50 MeV, the cross sections for producing ^{87}Zr and ^{86}Zr via the α2n- and α3n-out channels are predicted to be 127 mb and 82 mb, respectively. The partial γ-ray cross sections for the $13/2^+\rightarrow9/2^+$ and $2^+\rightarrow0^+$ ground state transitions are predicted to be factors of 4–5 greater than observed, as shown in Figure 8. For ^{89}Zr, at 50 MeV, the production cross section is due to primarily the 2p2n-out channel, and is predicted to be 66 mb, but the partial $13/2^+\rightarrow9/2^+$ γ-ray cross section (see Figure 9) is observed to be a factor of 6 greater than calculated. Therefore, the under-prediction of the 2pxn process for higher neutron bombarding energies is likely a direct result of the over-prediction of the αxn process. At lower neutron bombarding energies, the cross sections for α–particle emission are much *less* than observed. It is hoped that the present work will stimulate further investigation into complex-particle emission in high-energy reactions, an area that clearly needs much attention.

While it might be thought that the use of a white source of neutrons would render it impossible to determined the life times of levels, this is, in fact not the case. Very long-lived isomeric states, on the order of 100 μs to 10 ms, can be observed to decay during the beam-off period and their lifetime can be determined. For shorter lived isomeric states, less than several hundred ns, it is possible to extract their decay curves for times that correspond to neutron energies below their reaction threshold. An example of this is shown in Figure 10.

The result of the investigation into the reaction dynamics and comparisons with GNASH calculations has been submitted to TID, and will be submitted to Physical Review C [Gar00b]. It was also presented at the Division of Nuclear Physics of the American Physical Society Meeting in Asilomar, CA in Oct. 1999 [Gar99a], and further results will be presented at the American Chemical Society National Meeting in San Francisco, Mar. 2000 [Gar99b].

Reference:

[lis87] C.J. Lister et al.,, Phys. Rev. Lett. **59**, 12709 (1987).
[ber98]L.A. Bernstein et al., Phys. Rev. C **57** R2799 (1998). UCRL-ID-130176
[ber00]L.A. Bernstein et al., to be submitted to Phys. Rev. C–Rapid Comm.-Spring 2000.
[mcn98] D.P. McNabb et al., Bull. Am. Phys. Soc. 43, 1550 (1998). UCRL-JC-131734 Abs
[mcg99] C.A. McGrath et al., Bull. Am. Phys. Soc. (1999). UCRL-JC-134767 abs.
[Sin92] P. Singh *et al.*, Phys. Rev. C **45**, 2161 (1992).
[Gar00a] P.E. Garrett *et al.*, Phys. Rev. C, *submitted.* UCRL-JC-136968.
[Gar99a] P.E. Garrett *et al.*, Bull. Am. Phys. Soc. (1999). UCRL-JC-134769 Abs.
[You99] W. Younes *et al.*, Abs. of Capt. Gamma-ray Symp. Sept. 1999. UCRL-JC-135097 Abs.
[You00] W. Younes *et al.*, *Proceedings of the 10th International Symposium on Capture Gamma-ray Spectroscopy and Related Topics,* Sante Fe, NM, 1999, ed. S. Wender, to be published by AIP. UCRL-JC-135097.
[Gar00b] P.E. Garrett *et al.*, Phys. Rev. C, *to be submitted.*
[Gar99b] P.E. Garrett, Abs. of the ACS National Meeting, San Francisco, Mar. 2000. UCRL-JC-136253 Abs.

Personnel Funded by this Project:

Name	Position	Period Funded
Lee Bernstein	Staff Scientist (P.I.)	FY98-FY99
Paul Garrett	Term Staff (Co-P.I.)	FY98-FY99
John Becker	Senior Staff	FY98-FY99
Walid Younes	Term Staff	FY98-FY99
Dennis McNabb	Post-Doctoral	FY98
Chris McGrath	Post-Doctoral	FY99
Karl Hauschild	Post-Doctoral	FY98-FY99

Figure 1a: Even-mass Platinum nuclei observed as reported in [ber98]. The solid line is the results of HMS-ALICE calculations. Note the failure of the model to predict reaction cross sections for (n,xn) reactions with x≥7 (i.e., $^{188-184}Pt$).

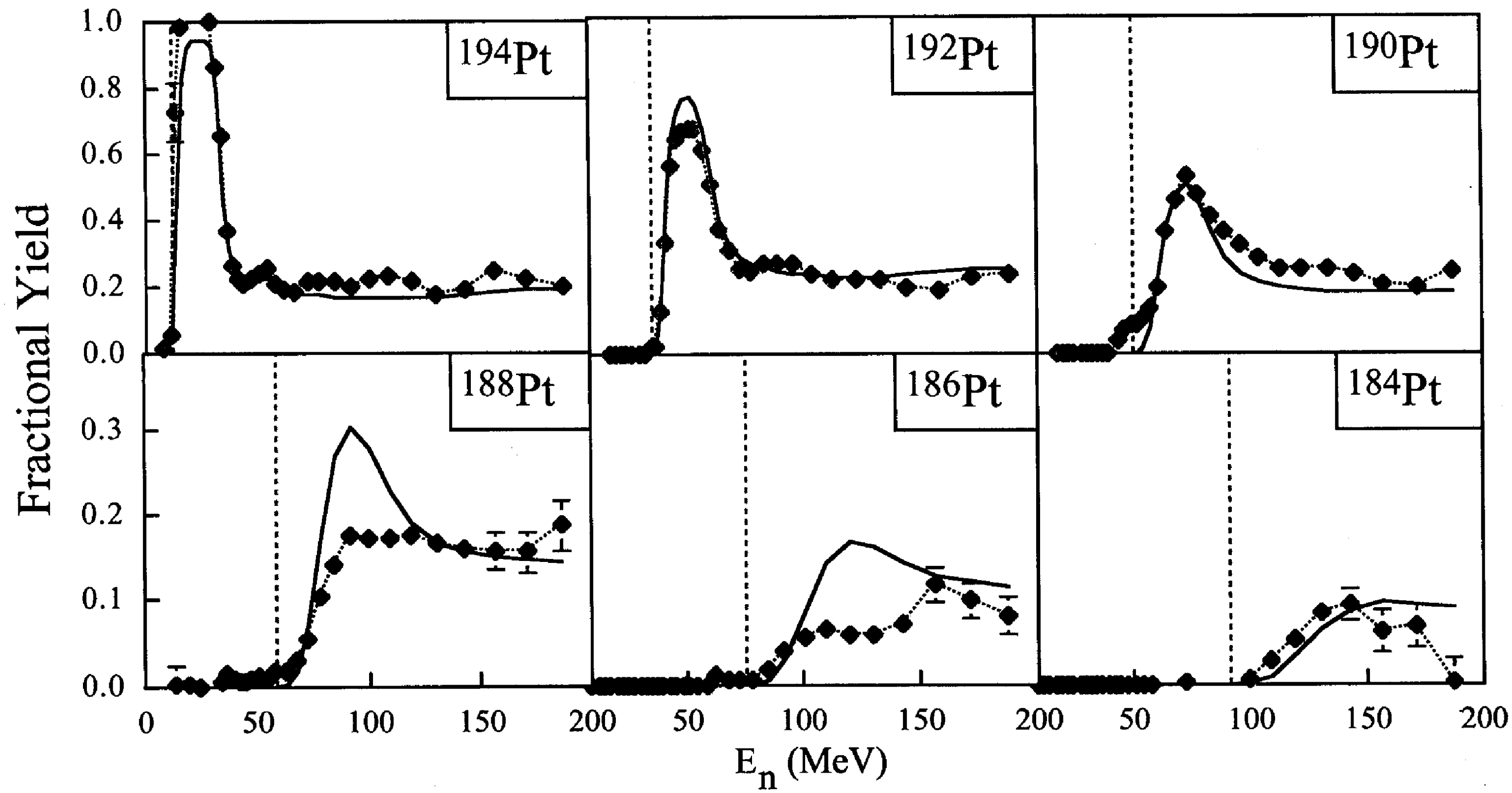


Figure 1b: Excited states populated in different even-mass Platinum nuclei populated in [ber98]. The higher temperature nuclear states (indicated in green) exhibit are populated very differently as a function of increasing neutron energy than the "cooler" states in the ground state band.

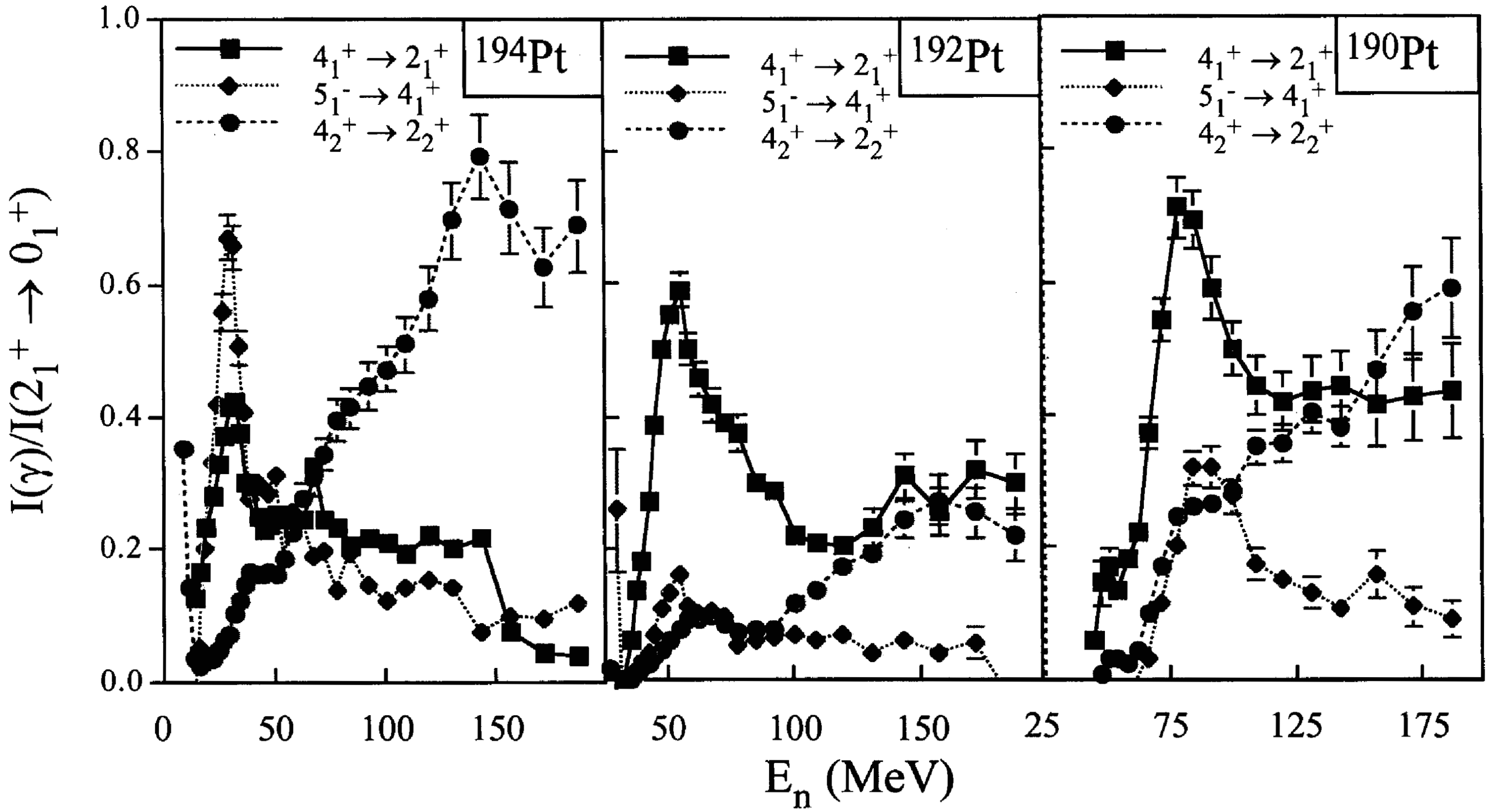


Figure 2: Nuclei populated in the ^{112}Sn experiment with GEANIE at LANSCE/WNR as reported by [mcn99].

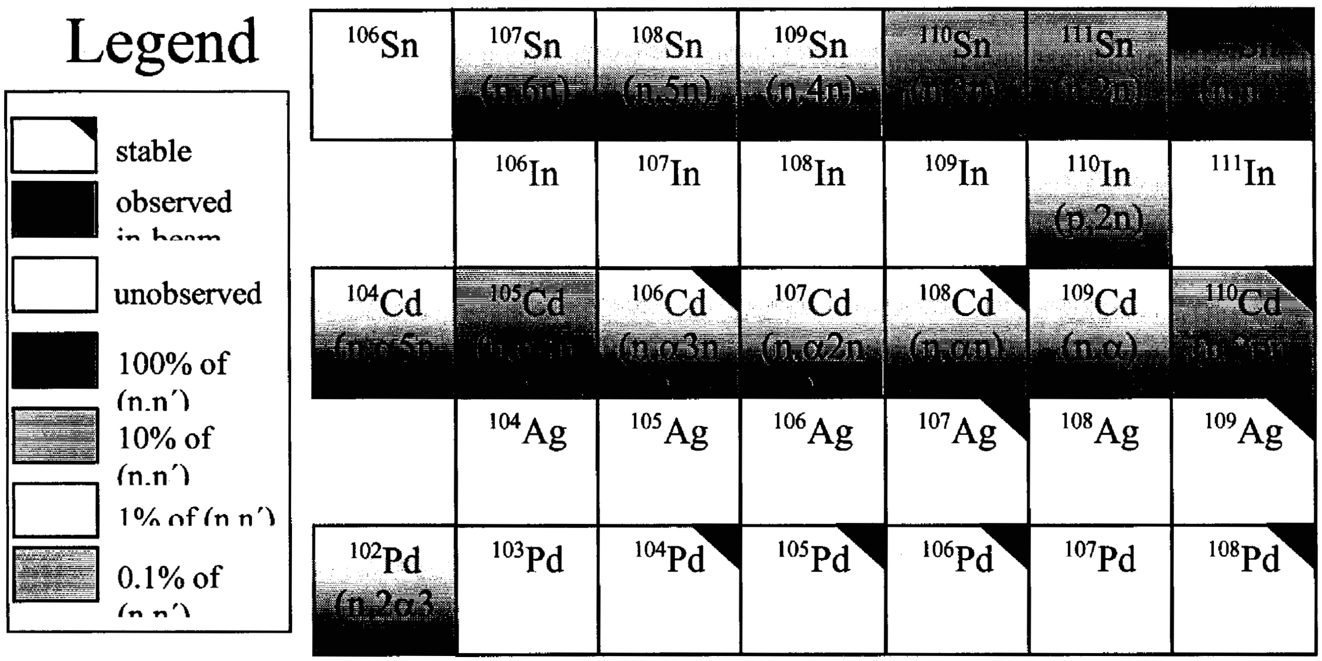


Figure 3: Normalized γ-ray partial cross sections for the $2 \rightarrow 0$ transitions in select even-mass nuclei populated in the 1997 GEANIE ^{112}Sn experiment as reported by [mcn99]. Pink points are GEANIE data, Triangles are HMS-ALICE calculations and Diamonds are GNASH calculations.

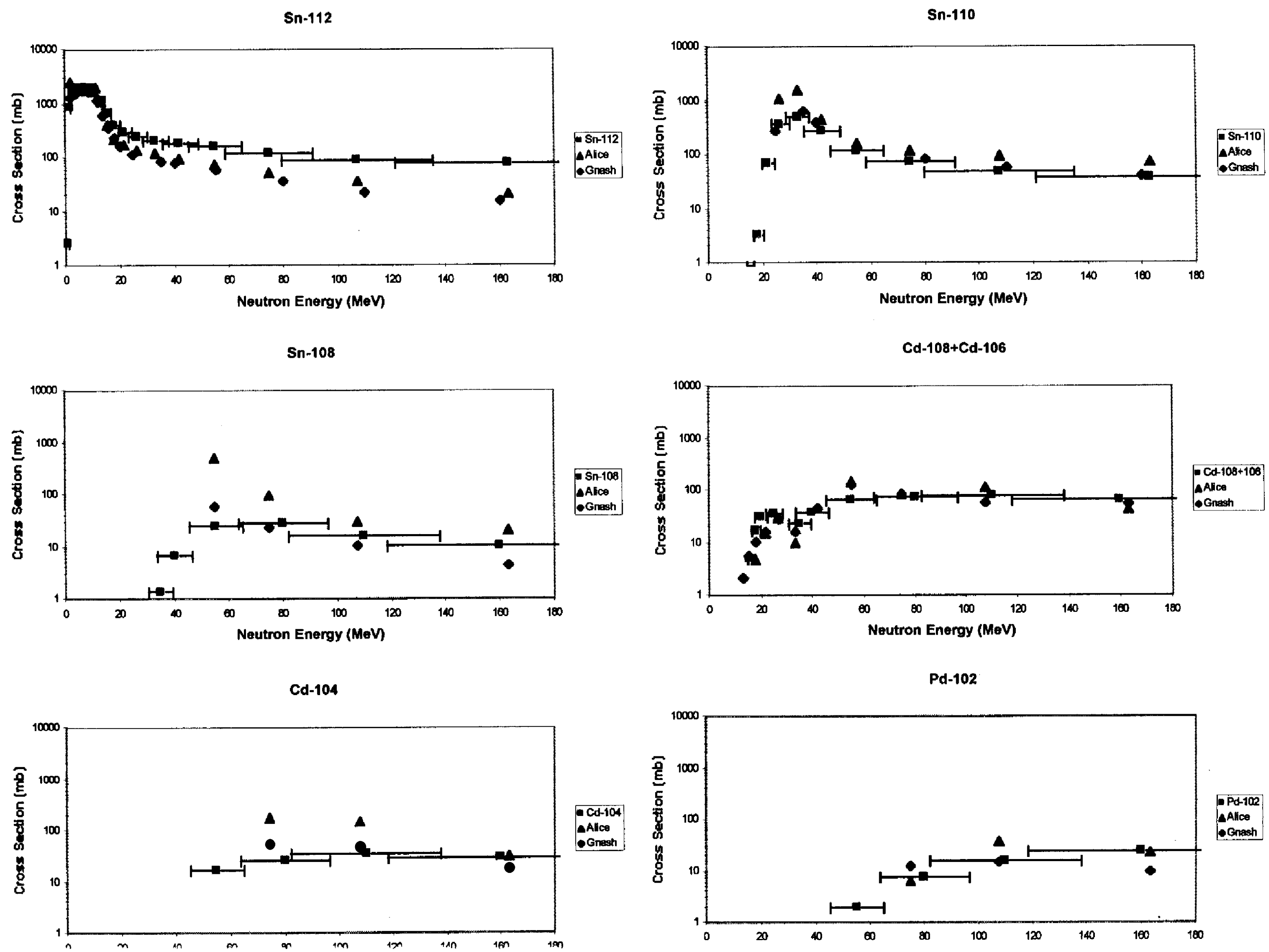
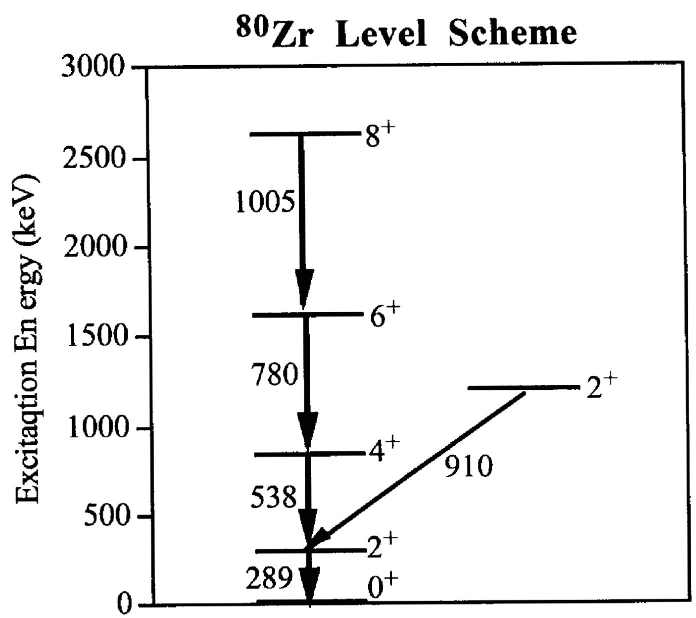


Figure 4: Tentative ^{80}Zr level scheme from the 1999 GAMMASPHERE experiment at Argonne National Laboratory. Spin Assignments are based on systematics from other nuclei.



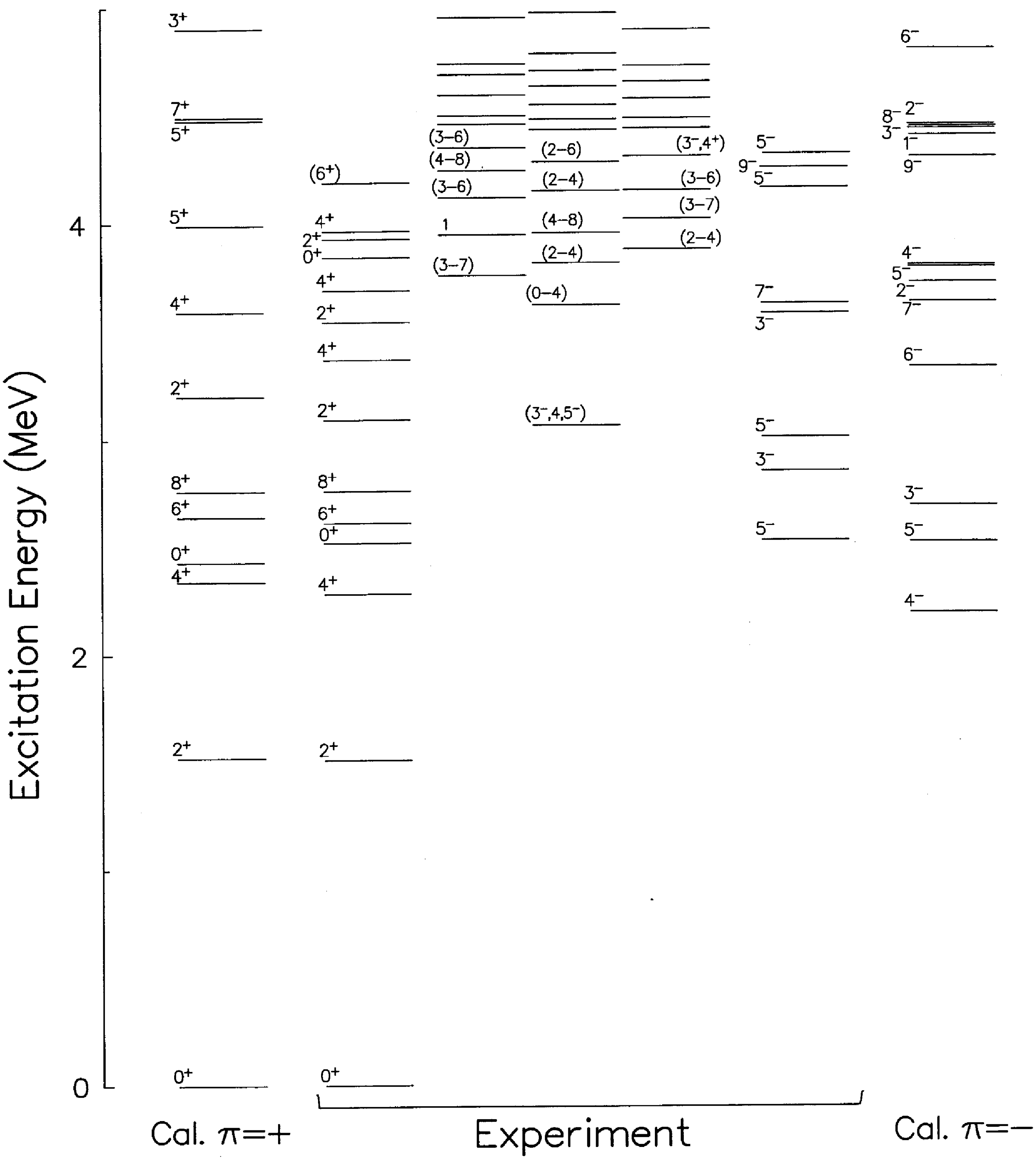


Figure 5. Experimental level scheme (center) compared with shell model calculations (outer columns) using the $g_{9/2}$,$p_{1/2}$ model space. The poorer agreement for the negative-parity states may be related to using the first 5^- level, recently suggested to be a one-phonon state, in the fitting procedure for the Hamiltonian.

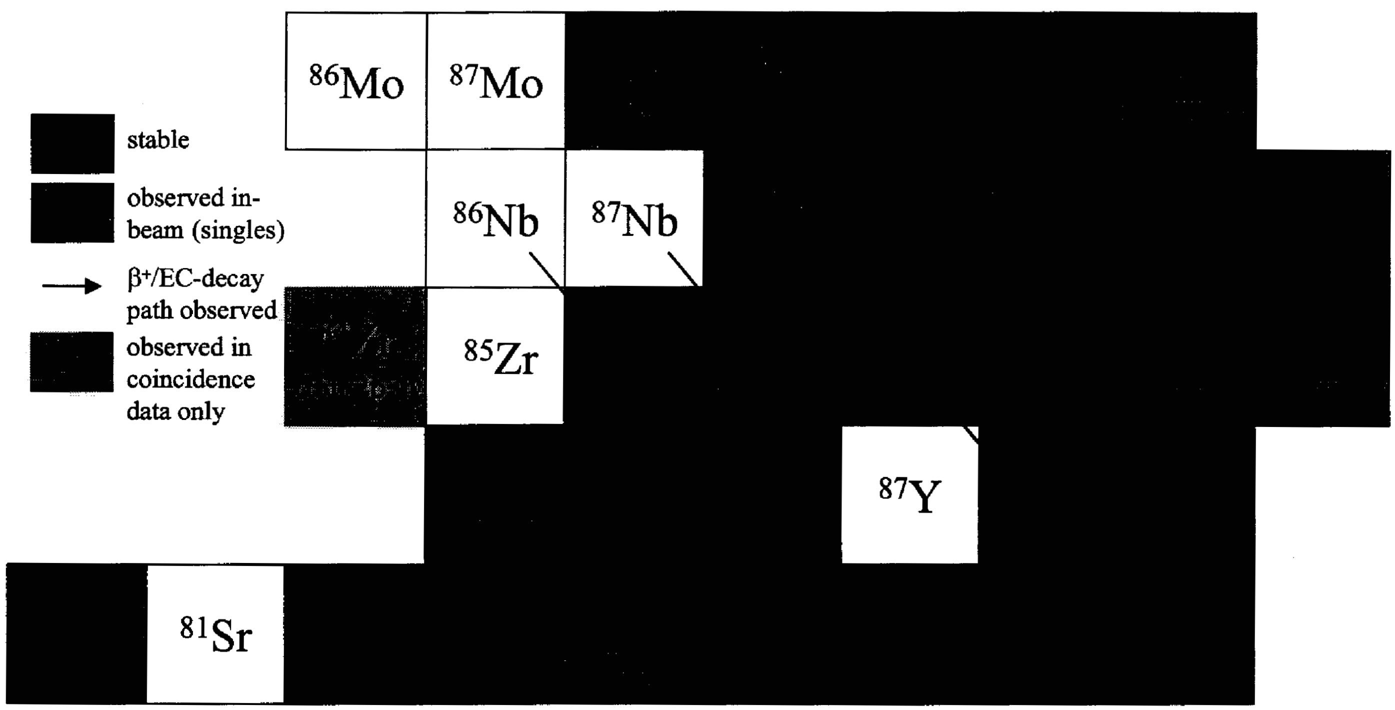


Figure 6. A partial chart of the nuclides showing the products observed following the bombardment of a target of ^{92}Mo with high-energy neutrons.

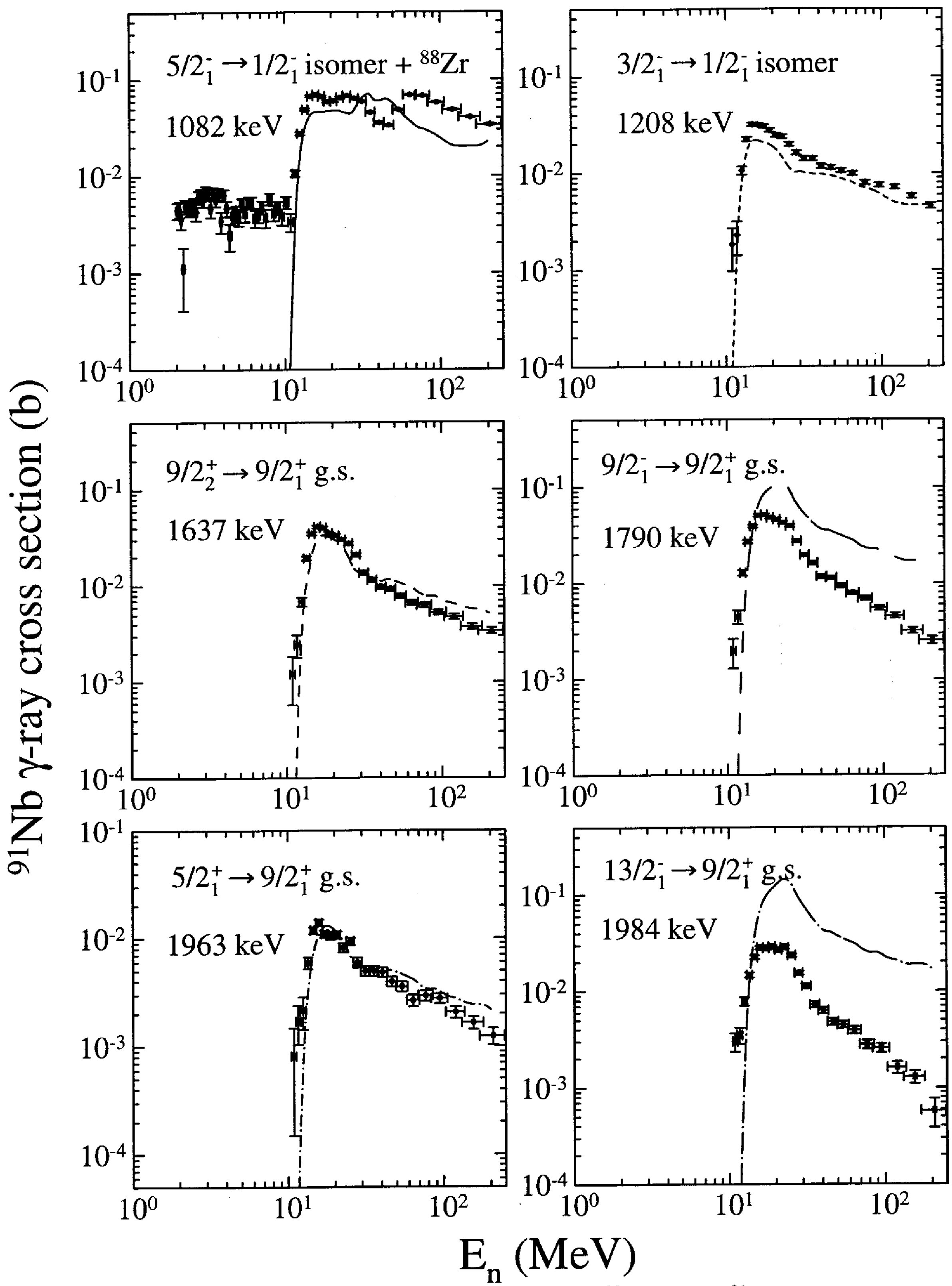


Figure 7. Excitation functions for γ rays originating from the ^{92}Mo(n,pnγ)^{91}Nb reaction. These data illustrate the effects of assumption used in the reaction modeling of equal level densities and spin distributions for the positive- and negative-parity states.

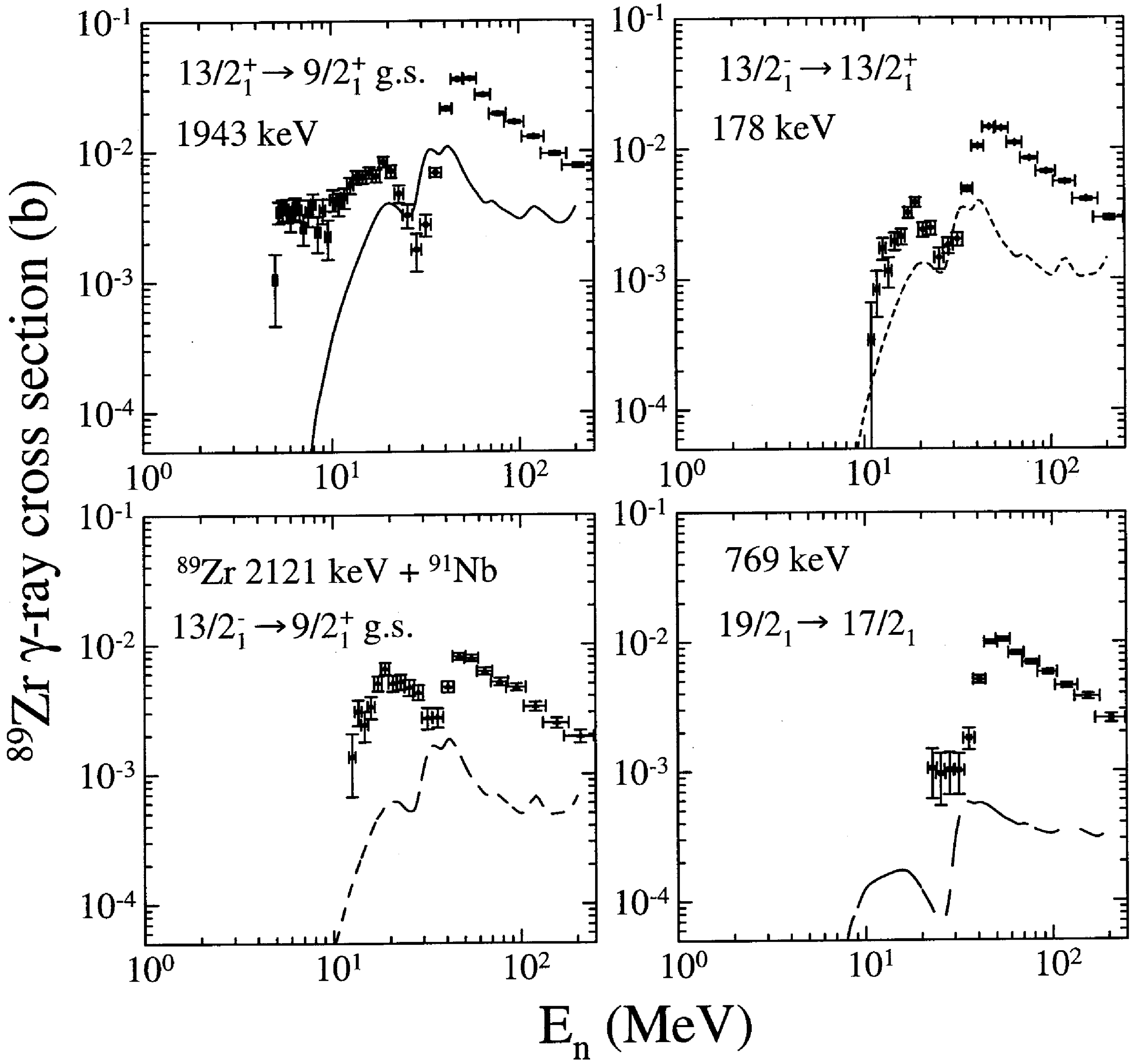


Figure 8. Excitation functions for γ rays originating from the ^{92}Mo(n,α/2p2nγ)^{89}Zr reaction. There is a clear distinction between α emission and the 2p2n process. The 2121-keV transition is unresolved from a ^{91}Nb γ ray, but it is believed to contribute less than 10% of the cross section above 30 MeV. Of note is the under-prediction of the cross section for α-emission, and that for the 2p2n-out channel at higher neutron bombarding energies.

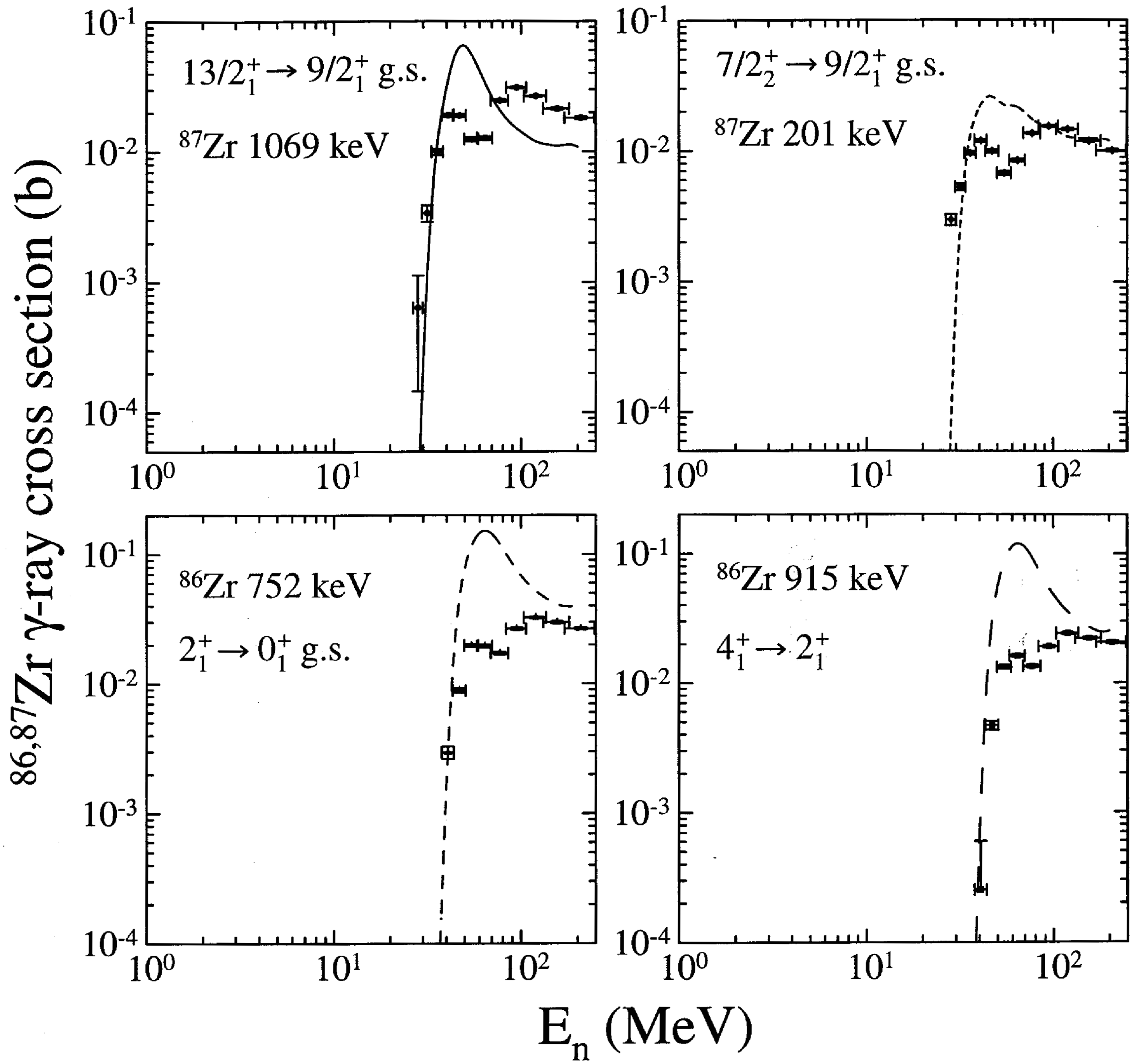


Figure 9. Excitation functions for γ rays originating from the ^{92}Mo(n,α2n/2p4nγ)^{87}Zr and ^{92}Mo(n,α3n/2p5nγ)^{86}Zr reactions. Of note is the gross over-prediction of the cross section for α-particle emission.

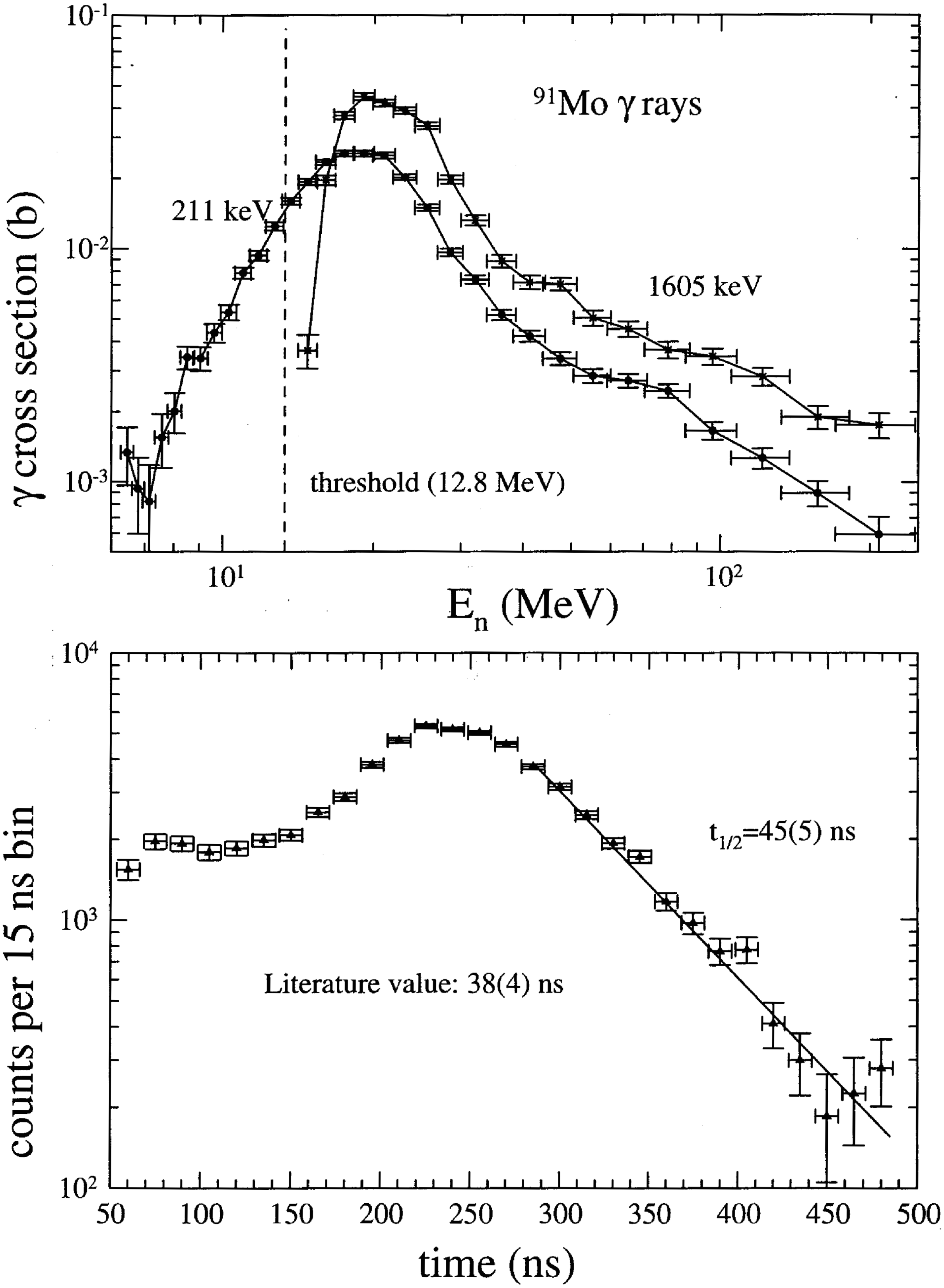


Figure 10. An example of the ability to determine life times of isomeric states by extracting their decay curves below the production threshold.